Paper ID : 1b002

DISTRIBUTED OPERATIONS FOR THE CASSINI/HUYGENS MISSION

Patricia Lock * *and Marc Sarrel* **

* *Jet Propulsion Laboratory*
California Institute of Technology
National Aeronautics and Space Administration
4800 Oak Grove Drive M/S 264-767, Pasadena, CA 91109-8099 USA
Patricia.D.Lock@jpl.nasa.gov, +1 (818) 393-5270, Fax +1 (818) 393-6236

** *Jet Propulsion Laboratory*
California Institute of Technology
National Aeronautics and Space Administration
4800 Oak Grove Drive M/S 230-250, Pasadena, CA 91109-8099 USA
Marc.A.Sarrel@jpl.nasa.gov, +1 (818) 393-7786, Fax +1 (818) 393-4669

ABSTRACT

The Cassini project employs a concept known as distributed operations which allows independent instrument operations from diverse locations, provides full empowerment of all participants and maximizes use of limited resources.

Science investigators and probe operators participate in the full range of operations from their home institutions. Each principal investigator (PI) is solely responsible for the design, construction, integration and flight operation of his or her own instrument, including mission planning, sequencing, instrument monitoring and science data acquisition, processing and analysis. Uplink and downlink processes have been developed expressly to support the distributed nature of the project.

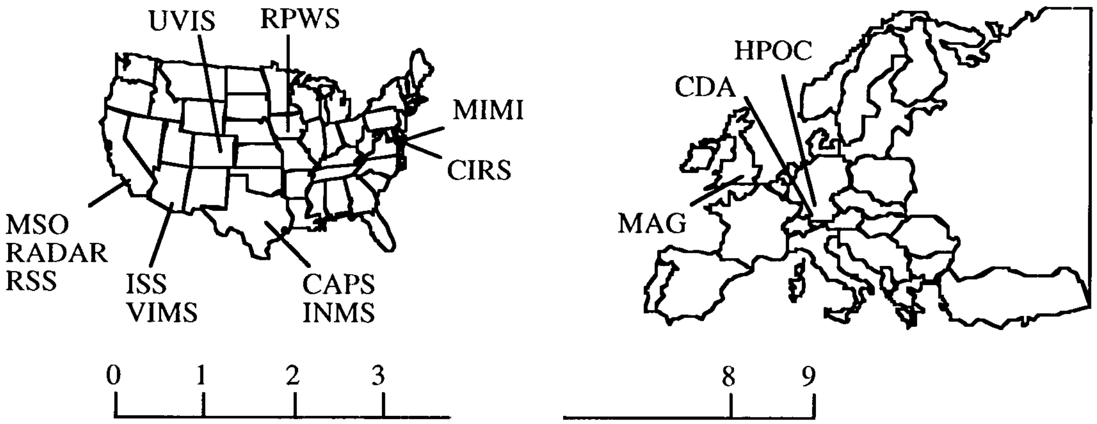
Each PI has been supplied with a Science Operations and Planning Computer (SOPC) to form a direct link between the center of operations at the Jet Propulsion Laboratory and the PI's own operational system. The SOPCs are designed to support each organization's communication needs, including command generation and submission, real-time monitoring, telemetry retrieval and voice communications.

1. INTRODUCTION

The Cassini/Huygens mission to the Saturnian system is a complex mission spanning eleven years of flight. The spacecraft was launched in October 1997 and is the last planned flagship solar system exploration mission. The Cassini orbiter carries twelve science instruments and the Huygens probe carries six. The Cassini mission's science objectives are to study Saturn itself, its rings, magnetosphere, icy satellites and moon Titan. The tour of Saturn will last four years, with two preceding years of approach science. The primary science objectives of the Huygens mission are to make a detailed, in situ study of Titan's atmosphere and to characterize the surface of the satellite along the descent ground track and near the landing site. The probe's primary mission is approximately two and a quarter hours long.

Cassini operations are conducted by the Cassini Mission and Science Operations Office (MSO) at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. Huygens Probe operations are conducted by the Huygens Probe Operations Centre (HPOC) at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The Cassini principal investigators and the probe operators are located in six US states and two European countries spanning a total of ten time zones (see Figure 1).

The principal challenges of distributed operations for Cassini are communications among participants across the range of time zones and computer security in a distributed system.



Time offset (hours)

Figure 1 Location of Distributed Operations Sites

2. DISTRIBUTED OPERATIONS DESIGN

2.1. DEFINITION OF DISTRIBUTED OPERATIONS

Cassini investigators and probe operators perform instrument operations from their home institutions which are, for the most part, located away from JPL. This is accomplished by conducting routine operations as a system, using a cohesive ground data system (GDS) and set of processes.

Crucial mission responsibilities have also been distributed among several authorities. Each principal investigator is now solely responsible for the design, construction, integration and flight operation of his or her own instrument, including mission planning, sequencing, instrument monitoring and science data acquisition, processing and analysis.

2.2. DESIGN OVERVIEW

The Cassini program chose to distribute operations for the following reasons:

- Cost savings - Remotely-located investigators no longer need instrument representatives at JPL. PIs represent themselves from their home institutions. Distributed responsibility removes communication/approval steps from operations processes and frees ground system resources.
- Empowerment - PIs are fully responsible for their instrument from design through operations, particularly all instrument monitor and command functions.
- The Huygens Probe is a separate project - The probe is operated from the HPOC in Darmstadt, Germany, interfacing with the rest of the project in the same manner as the PIs.

Distributed operations is made possible by advances in networking and computing technology. The empowerment of the principal investigators makes distributed operations successful. In the majority of previous JPL missions, investigators have performed flight operations through intermediaries. Some of these intermediaries worked directly for the PI. Others worked for the spacecraft health and safety owners at JPL and were not answerable to the PI. This added at least one extra step to the communication process. The old system sometimes added complexity to routine operations and created conflict among the participants, which have been avoided on Cassini.

For Cassini, the PIs have been responsible for the design, construction and integration of their instrument into the flight system. This has greatly increased the knowledge base of the operators and fulfilled a Cassini project goal that all developers, including the PIs, shall operate what they have developed.

Full empowerment and participation of the PIs also reduces cost. Allowing PIs to represent themselves eliminates the need for an intermediate layer of science personnel located at JPL. With fewer people in the communication loop, processes become streamlined.

2.2.1. GROUND DATA SYSTEM

2.2.1.1. GDS OVERVIEW

The Cassini ground data system is divided into downlink and uplink portions. A simplified version is shown in Figure 2. The uplink process is iterative. The Mission Sequence System (MSS) is used to plan spacecraft activities, design the sequence of commands to implement those activities and to translate the commands into the format that the spacecraft can execute. Files are exchanged through a file repository called the Central Database (CDB). Once the commands are translated into executable form, they are sent to the Deep Space Network (DSN) and radiated to the spacecraft.

The downlink process is linear. Telemetry is received at the spacecraft by the DSN. It is processed and then stored in the Telemetry Delivery System (TDS). When telemetry is being received by the DSN, the processed telemetry is made available to all users by a broadcast. The Data Monitor and Display (DMD) program is used to view the telemetry on this broadcast and check for telemetry limit violations. Users may also query any telemetry since launch from the TDS using the Telemetry Output Tool (TOT).

2.2.1.2. SCIENCE OPERATIONS AND PLANNING COMPUTERS

The SOPCs are a direct extension of the Cassini ground data system to the distributed operations (DO) sites. They use the same set of software as the Cassini computers at JPL. Each is linked to JPL by a 56 kbps dedicated serial line. All this allows the PIs to participate in mission operations as if they were at JPL. SOPCs eliminate duplication of science computing resources at JPL and promote PI empowerment and independence.

The SOPC is also the link between the Cassini GDS and each PI's own processing system. That processing system can be located directly on the SOPC or on the PI's own computing hardware. The investigator's system participates in the uplink and both the real-time and non-real-time downlink processes. The SOPC and associated software provide a flexible interface to the PIs' own processing systems.

2.2.2. MISSION OPERATIONS SYSTEM

2.2.2.1. PEOPLE

As in all cases, when performing work with many players in many locations, coordination is crucial. The Cassini flight project has created an operations position called the distributed operations coordinator (DOC). The DOC is on duty during regular JPL hours and when there are any off-shift instrument or probe activities. The DOC's role is to be an assured point of contact for DO site personnel to assist in their participation in operations, in the use of their SOPC, and to be their legs at JPL, when necessary. The DOC, located in the Cassini mission support area (MSA), knows both the local and distributed personnel and plays an important role in facilitating communication among the participants. The DOC is also the primary conduit for anomaly resolution with the DO sites.

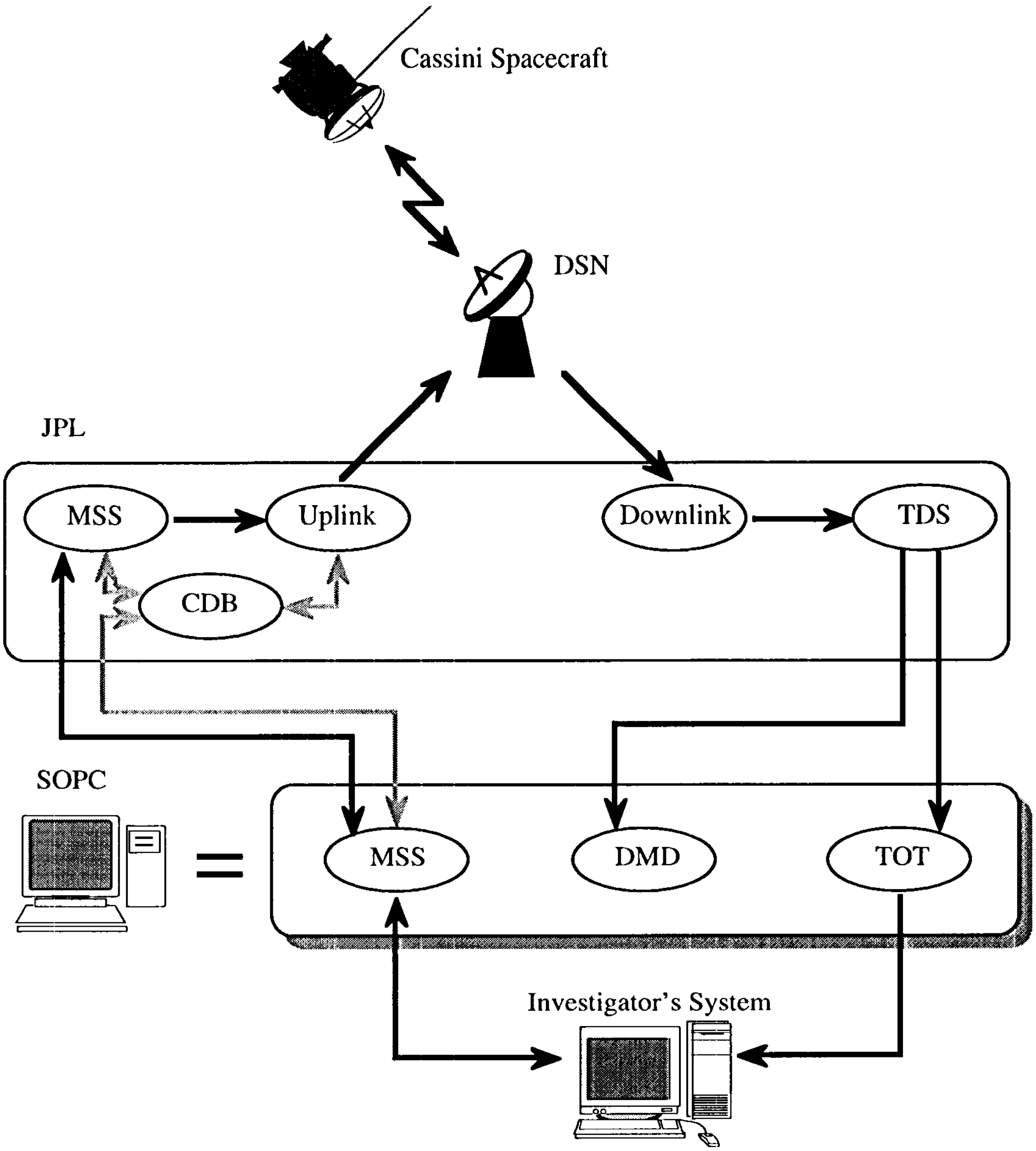


Figure 2 Cassini Ground Data System

2.2.2.2. PROCESSES

For the distributed uplink process, the concept of a virtual team has been developed. A virtual team is constituted of the stake holders and technical experts concerned with the activities to be conducted in a given mission period or phase. At the completion of that phase, the team is disbanded. This allows the composition of the virtual team to change based on the needs of a specific period. Virtual teaming supports distributed operations by its very nature. Those with the planning or commanding responsibility participate on their own behalf, when there is need and are not required to participate otherwise.

The downlink data distribution process employs a distributed client-server architecture. During times when telemetry is being received from the spacecraft, users may monitor that telemetry in real-time on their SOPCs. Real-time telemetry is always monitored for limit violations at JPL.

Procedures are in place to quickly notify the PIs if any instrument limits are violated. At any time, users may retrieve telemetry of interest to them and have it delivered to their SOPC. In this way, the downlink process is controlled by the SOPC user.

3. OPERATIONS IN A DISTRIBUTED ENVIRONMENT

3.1. UPLINK

3.1.1. PLANNING

The Cassini mission planning process begins six months before start of execution of the sequence on the spacecraft. It takes its input from the science planning process which precedes it. Its main activity is a series of weekly teleconferences with all participants in the mission planning virtual team (MPVT). Required and approved activities for a phase are fleshed out, new activity requests are entertained and resources are allocated. Electronic files for submission or review are copied to the CDB for access by all flight team members. The output of the mission planning process is the input to the sequencing process.

3.1.2. COMMAND GENERATION & SUBMISSION

Sequence and command generation begins eight weeks prior to sequence execution. The process is run by the sequence virtual team (SVT). Each subsystem or instrument submits a subsequence of their own commands. Shared items are contributed by the SVT leader. The subsequences are combined to form the final integrated sequence and that sequence is validated by all. Files are submitted and retrieved for review through the CDB. After uplink of the sequence, any additional commands needed, i.e. real-time commands, are generated using a similar but much abbreviated process.

In the future, an automated command processor will watch for file deliveries to the CDB and perform the software processing necessary to prepare them for uplink. This will speed up the generation process and allow participants to submit command requests during their own prime shift.

3.2. DOWNLINK

3.2.1. REAL-TIME TELEMETRY MONITORING

Telemetry is monitored in real-time while the DSN is receiving data from the spacecraft. Monitoring is performed in order to assess the health and safety of the instruments and spacecraft, to confirm the correct execution of the sequence or real-time commands and to evaluate the performance of the flight hardware.

The investigators monitor telemetry in real time with tools on their SOPC and with their own processing systems. DMD provides the capability to monitor the engineering data from their instrument and the spacecraft. Their own processing system usually handles instrument engineering and science data.

To simplify SOPC operations, special arrangements have been made to forward the real-time telemetry directly to the SOPCs. Because of limited bandwidth, investigators must choose with care the exact subset of telemetry sent to their SOPC.

3.2.2. NON-REAL-TIME TELEMETRY RETRIEVAL

Non-real-time telemetry retrieval can be done at any time. All telemetry data for the mission is stored in the TDS server. Users retrieve the data types they need for the time ranges in which they are interested. This is typically done to make a clean and complete data set for either engineering or scientific processing, analysis and archive. The networks, computers and software based on a client-server model allow users at the distributed operations sites the same access to data as users at JPL.

3.3. SCIENCE DATA PROCESSING

Scientists retrieve their science data from the TDS in the same way that they retrieve all other telemetry. For instruments built at JPL, the first step of processing is done at JPL, before the data are distributed to the scientists. The rest of the scientists work directly from the unprocessed data. Most science data are processed on the investigator's own system rather than on the SOPC.

3.4. COMMUNICATIONS

To support its method of distributed operations, Cassini uses a variety of communications technologies. The uplink and downlink processes have been designed to require distributed participation. Each SOPC is equipped with a dedicated voice line that connects the SOPC user to mission controllers and engineers at JPL. This is primarily to support real-time operations including real-time telemetry monitoring, real-time commanding and ground data system tasks. In some cases timely notification of project members is essential.

Almost all members of the flight team at JPL have pagers and at least two people at each distributed operations site have pagers as well. The pagers support short text messages as well as traditional numeric ones. In Europe, where our pager service provider has no coverage, we substitute locally obtained cell phones or positions which are staffed continuously.

The operations and development meetings that are held routinely make use of commercially available communications technology. All members of the project have the ability to set up a teleconference, without operator intervention, from their office or meeting room. Some meeting rooms, including one at each distributed operations site, also have video conferencing capabilities. All of these meetings are supported by email and fax.

4. CHALLENGES OF DISTRIBUTED OPERATIONS

4.1. TIME ZONES & SCHEDULING

The most difficult challenge of distributed operations for Cassini is the range of time zones among participants and the fact that prime shift at the European sites does not overlap with prime shift at JPL. Meetings, training and validation activities were carefully coordinated to accommodate all the participants' workdays.

Remote locations and teleconferencing reduce face to face contact. Participants who do not get to know each other communicate less easily. The distance tends to divide the culture into two groups, those at JPL and those at the distributed operations sites. To alleviate this, a monthly Science Operations Working Group (SOWG) is held at JPL, with attendees welcome to attend in person or by tele- or videoconference. In this way most of the remote personnel travel to JPL several times a year. Additional working meetings and social activities are scheduled in conjunction with the SOWG, but at the travellers' convenience. PIs also travel to JPL for other less frequent technical reviews and meetings.

4.2. NETWORK CONSIDERATIONS

The goal of the distributed system is to provide reliable access while protecting both the SOPCs and the JPL operational system. Achieving ease of use within the boundaries of good security practice is fundamental to our implementation. We have taken strong measures to guard against denial of service attacks and against alteration, deletion or disclosure of sensitive information. We routinely reevaluate and enhance our security measures in response to new threats and evolving technology.

Another constraint on the Cassini distributed ground data system is the limited bandwidth of the data lines between JPL and the distributed operations sites. This is a tradeoff between functionality and cost. The lines we use currently are 56 kbps. For the tour phase of the mission, a new analysis will need to be done to determine if this size will be sufficient.

4.3. ANOMALY RESPONSE

The Cassini architecture dictates that the distributed elements of the project participate in the response to spacecraft or ground anomalies. This includes being fully informed of events and empowered to make decisions regarding their instruments. The anomaly procedure clearly spells out the roles and responsibilities of the flight team members. It also specifies the initial series of actions as well as the activities that must be taken over the longer term until the anomaly is resolved. Upon identification of an anomaly, a short meeting is held to discuss the nature and determine the scope (small, medium or large) based on predefined criteria. Then, representatives of all relevant organizations within the project are notified. The method and timeliness of the notification depends on the scope of the anomaly. The distributed operations coordinator notifies representatives of the science instruments and probe.

An anomaly team is then convened, its membership determined by the nature of the anomaly. The anomaly team functions as a virtual team in the same way as the sequence and mission planning virtual teams. It is composed of members from different organizations within the project who come together for a short period of time to resolve the anomaly. Throughout the process, the distributed operations coordinator is responsible for informing the distributed operations sites of the results of anomaly meetings and the schedule of upcoming meetings. Any commanding of the spacecraft during an anomaly follows the nominal process.

4.4. MISSION DURATION AND CONTINUITY

In any distributed operations environment, communication and information distribution is difficult. For Cassini, this is made even more difficult by the long mission duration. Cassini has a seven year cruise before its four year tour of the Saturn system. In that eleven year span, many personnel changes are expected. At JPL, changes will be manageable, since JPL has a core of long-term Cassini personnel and also a large pool of operational talent from which to pull replacements.

At the distributed operations sites, this is not usually the case. At many sites there are only two trained individuals. If one leaves, much experience will be lost and only the remaining flight team member will be available to train the replacement. To mitigate this, operational procedures and other project documents have been made available electronically to authorized personnel. A library of training videos was also created and many sites maintain their own copies of the most pertinent training videos.

During the eleven years, technology will change drastically. Cassini has planned for two full GDS hardware upgrades during the life of the mission. Planning for these will begin very early to take into account the difficulties of coordinating the upgrades with ongoing operations and of shipping hardware around the world.

5. CONCLUSIONS

The Cassini mission has been using distributed operations since the assembly of the spacecraft. As with any system, we are always learning new ways to improve it. Other JPL missions have used some parts of what Cassini calls distributed operations, but Cassini is the only mission to take the concept to this level. The top level goal of designing a mission with distributed operations is to reduce overall cost by empowerment of the participants.

However, along with empowerment come added responsibilities. These responsibilities are often made more difficult to meet for logistical reasons of distance and time. It has taken some effort to find the right balance of workload between the project members at JPL and those at the distributed operations sites. This is especially true because of the relatively small workforce at each site.

Since the goal of distributed operations is to reduce overall cost, it is acceptable to have certain areas of increased cost. These appear in the design of processes but especially so in support of the SOPCs. It is difficult to administer and maintain such computing systems in so many locations. Smaller and shorter missions should be guided by the same principals, but should consider alternate implementations that do not incur the same overhead. For example, Cassini is experimenting with a web based telemetry viewer that has already been used successfully on other missions. Distributed operations will only become easier and more natural as computing and network technology improves. Distributed operations may add complexity and cost to some tasks, but the benefits far outweigh the costs.

ACRONYM LIST

CAPS	Cassini Plasma Spectrometer
CDA	Cosmic Dust Analyzer
CDB	Central Database
CIRS	Composite Infrared Spectrometer
CM	Configuration Management
DMD	Data Monitor and Display
DO	Distributed Operations
DOC	Distributed Operations Coordinator
DSN	Deep Space Network
ESOC	European Space Operations Centre
GDS	Ground Data System
HPOC	Huygens Probe Operations Centre
INMS	Ion and Neutral Mass Spectrometer
ISS	Imaging Science Subsystems
JPL	Jet Propulsion Laboratory
kbps	kilobits per second
MAG	Dual Technique Magnetometer
MIMI	Magnetospheric Imaging Instrument
MPVT	Mission Planning Virtual Team
MSA	Mission Support Area
MSO	Mission and Science Operations Office
MSS	Mission Sequence System
PI	Principal Investigator
RADAR	Radio Detecting and Ranging
RPWS	Radio and Plasma Wave Spectrometer
RSS	Radio Science Subsystem
SOPC	Science Operations and Planning Computer
SOWG	Science Operations Working Group
SVT	Sequence Virtual Team
TDS	Telemetry Delivery System
TOT	Telemetry Output Tool
UVIS	Ultraviolet Imaging Spectrograph
VIMS	Visual and Infrared Mapping Spectrometer

REFERENCES

1. Cassini Home Page (http://www.jpl.nasa.gov/cassini).
2. Cassini Mission Plan, Jet Propulsion Laboratory, California Institute of Technology, Revision G, Change 1, PD 699-100, JPL D-5564, 3 June 1997.
3. Cassini Teachers' Resource Guide (http://www.jpl.nasa.gov/cassini/MoreInfo/teaguide.html).
4. Huygens Home Page (http://www.estec.esa.nl/spdwww/huygens).
5. Sarrel, M., "Cassini Science Operations and Planning Computer design," Proc. SPIE Vol. 2803, p. 222-233, Cassini/Huygens: A Mission to the Saturnian Systems, Linda Horn; Ed., 1996.

We would like to thank the other members of the Cassini Distributed Operations Interface element. Much of the material in this paper reflects their work. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.